
Resolving the inner active accretion disk around the Herbig Be star MWC 147 with VLTI/MIDI+AMBER spectro-interferometry

S. Kraus, Th. Preibisch, and K. Ohnaka

Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, 53121 Bonn,
Germany skraus@mpifr-bonn.mpg.de

Summary. We studied the geometry of the inner (AU-scale) circumstellar environment around the Herbig Be star MWC 147. Combining, for the first time, near-(NIR, K band) and mid-infrared (MIR, N band) spectro-interferometry on a Herbig star, our VLTI/MIDI and AMBER data constrain not only the geometry of the brightness distribution, but also the radial temperature distribution in the disk. For our detailed modeling of the interferometric data and the spectral energy distribution (SED), we employ 2-D radiation transfer simulations, showing that passive irradiated Keplerian dust disks can easily fit the SED, but predict much lower visibilities than observed. Models of a Keplerian disk with emission from an optically thick inner gaseous accretion disk (inside the dust sublimation zone), however, yield a good fit of the SED and simultaneously reproduce the observed NIR and MIR visibilities. We conclude that the NIR continuum emission from MWC 147 is dominated by accretion luminosity emerging from an optically thick inner gaseous disk, while the MIR emission also contains strong contributions from the outer dust disk.

1 Introduction and observations

Herbig Ae/Be (HAeBe) stars are intermediate-mass objects which are still accreting material, probably via a circumstellar disk composed of gas and dust. Understanding the structure of these disks and the processes through which they interact with the central star is critical for our understanding of the formation process of stars. Since, until recently, the spatial scales of the inner circumstellar environment (a few AU) were not accessible to infrared imaging observations, conclusions drawn on the 3-D geometry of the circumstellar material were mostly based on the modeling of the SED (e.g. Hillenbrand et al. [1]). However, these fits are known to be ambiguous (e.g. Men'shchikov & Henning [2]) and have to be complemented with spatial information, as provided by infrared interferometry.

The first systematic studies of HAeBes using the technique of infrared long-baseline interferometry have revealed that for most HAeBes the NIR

size correlates with the stellar luminosity L following a simple $R \propto L^{1/2}$ law. This suggests that the NIR continuum emission mainly traces hot dust at the inner sublimation radius. However, for more luminous Herbig Be stars, the NIR-emitting structure is more compact than predicted by the size-luminosity relation (Monnier et al. [3]).

To further investigate the origin of the “undersized” Herbig Be star disks, we observed the Herbig Be star MWC 147 with the VLTI. First infrared interferometric observations of this star by Akeson et al. [4] indicated that the NIR-emitting region is surprisingly compact (~ 0.7 AU, assuming a uniform disk profile). In the course of three ESO open time programmes and using the 8.2 m UT telescopes, we obtained seven VLTI/MIDI measurements and one VLTI/AMBER measurement. The MIDI observations cover baseline lengths between 39 and 102 m. From the AMBER data, one wavelength-dependent visibility, corresponding to a 101 m baseline, could be extracted. For our modeling of MWC 147, we adopt the stellar parameters by Hernández et al. [5], namely a spectral type of B6, a distance of 800 pc, a bolometric luminosity of $1550 L_{\odot}$, a mass of $6.6 M_{\odot}$, and a stellar radius of $6.63 R_{\odot}$.

2 The power of joint NIR/MIR spectro-interferometry

The VLTI instruments AMBER and MIDI combine the high spatial resolution achievable with infrared interferometry with spectroscopic capabilities, measuring the fringe visibility as a function of wavelength. As circumstellar disks exhibit a temperature gradient, different spectral channels trace different spatial regions. Therefore, spectro-interferometric observations, which cover a sufficiently large wavelength range, can constrain not only the disk geometry, but also the radial temperature profile of the disk. For the investigation on YSO disks, the NIR and MIR wavelength regimes are particularly well suited since the NIR wavelength regime ($\sim 2 \mu\text{m}$) is most sensitive to the thermal emission from dust located at the dust sublimation radius ($T \approx 1500$ K, a few AU from the star), while MIR wavelengths ($\sim 10 \mu\text{m}$) trace dust with a temperature of several hundred Kelvin, located a few 10 AU from the star (see Fig. 1).

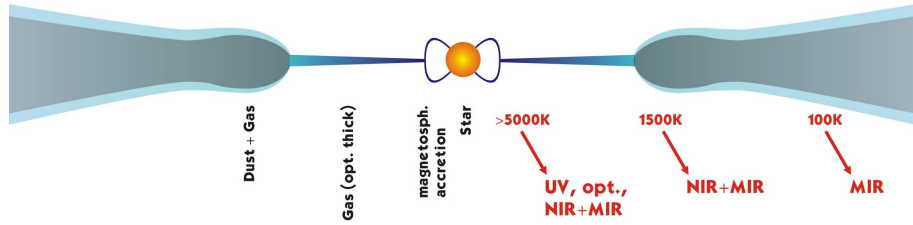


Fig. 1. Illustration of the inner environment of H AeBe stars. Due to the different temperatures, spectro-interferometry can disentangle multiple emission components.

3 Radiative transfer modeling

As a first step of analysis, we compared the interferometric data to commonly used analytic disk models with a simple temperature power-law ($T(r) \propto r^{-\alpha}$, with $\alpha = 3/4$ or $1/2$). Using the assumption that each disk annulus radiates as a blackbody, we can compute the wavelength-dependence of the disk size corresponding to these analytic models and find that they cannot reproduce the measured NIR and MIR-sizes simultaneously (see Fig. 2).

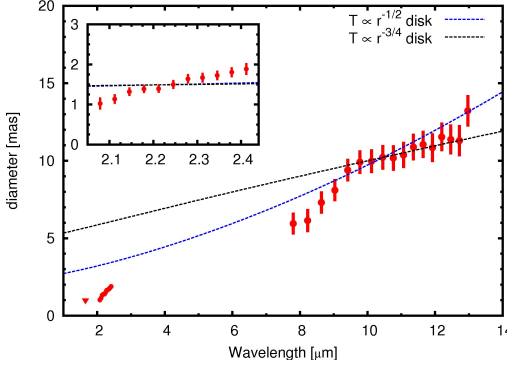


Fig. 2. Comparing the wavelength-dependent disk size of MWC 147 (as derived from one of our VLTI/AMBER+MIDI measurements) with the wavelength-dependent disk size predicted by standard temperature power-law disk models, we find that these models cannot reproduce our measurements. In this figure, the disk model was scaled to match the measured MIR size.

Therefore, we applied a more sophisticated modeling approach using the *mcsim_mpi* 2-D radiative transfer code (Ohnaka et al. [6]). For each model, we first check the agreement with the SED of MWC 147 and then fit the spectro-interferometric visibilities (see Kraus et al. [7] for details). The dust density distribution of the accretion disk in our models resembles a flared, Keplerian-rotating disk with a radial density distribution of $\rho(r) \propto r^{-3/2}$, which extends from the dust sublimation radius to 100 AU. In order to reproduce the shape of the SED, we found that, in addition to the disk, an extended envelope is required, for which we use the radial density distribution $\rho(r) \propto r^{-1/2}$.

Fig. 3 shows model images, the SED, as well as the visibilities corresponding to our best-fit model of a passive, irradiated accretion disk. Although irradiated disks are able to reproduce the SED of MWC 147, they predict visibilities which are much smaller than the measured visibilities ($\chi_r^2 \approx 26$) and are therefore in strong conflict with our interferometric measurements.

In passive circumstellar disks, the infrared emission is generally assumed to originate almost entirely from dust; the emissivity of the inner, dust-free gaseous part of the disk, at radii smaller than the dust sublimation radius, is negligible. In an actively accreting disk, on the other hand, viscous dissipation of energy in the inner dust-free gaseous part of the accretion disk can heat the gas to high temperatures and give rise to significant amounts of infrared emission from optically thick gas. The inner edge of this gas accretion disk is expected to be located a few stellar radii above the stellar surface, where the hot gas is thought to be channeled towards the star via magnetospheric accretion columns. While the magnetospheric accretion columns are too small to be resolved in our interferometric data ($3 R_\star$ correspond to 0.09 AU or 0.12 mas),

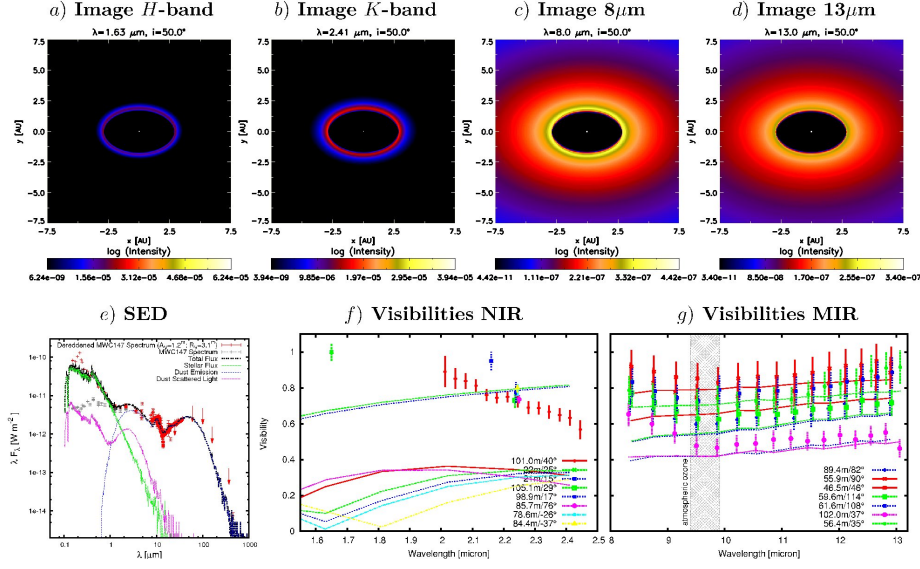


Fig. 3. Model images (a-d), SED (e), and NIR/MIR visibilities f-g corresponding to our best-fit radiative transfer image of an irradiated dust disk geometry. The poor agreement between measured and model visibilities ($\chi_r^2 \approx 26$) indicates that passive disk models can be ruled out.

infrared emission from hot gas between the dust sublimation radius and the stellar surface should be clearly distinguishable from the thermal emission of the dusty disk due to the different temperatures of these components and the resulting characteristic slope in the NIR- and MIR- visibilities.

Since MWC 147 is a quite strong accretor ($\dot{M}_{\text{acc}} \approx 10^{-5} M_\odot \text{ yr}^{-1}$; Hillenbrand et al. [1]), significant infrared emission from the inner gaseous accretion disk is expected. Muzerolle et al. [8] found that even for smaller accretion rates, the gaseous inner accretion disk is several times thinner than the puffed-up inner dust disk wall and is optically thick (both in radial as well as in the vertical direction). In order to add the thermal emission from the inner gaseous disk to our radiative transfer models, we assume the radial temperature power-law by Pringle [9]. Including the accretion luminosity from an inner gaseous disk in the model strongly improves the agreement between model predictions and observed visibilities. With a flared disk geometry and an accretion rate of $\dot{M}_{\text{acc}} = 9 \times 10^{-6} M_\odot \text{ yr}^{-1}$, both the SED and the interferometric visibilities are reproduced reasonably well ($\chi_r^2 = 1.0$, see Fig. 4).

4 Conclusions and outlook

Our VLTI interferometric observations of MWC 147 constrain, for the first time, the inner circumstellar environment around a Herbig Be star over the

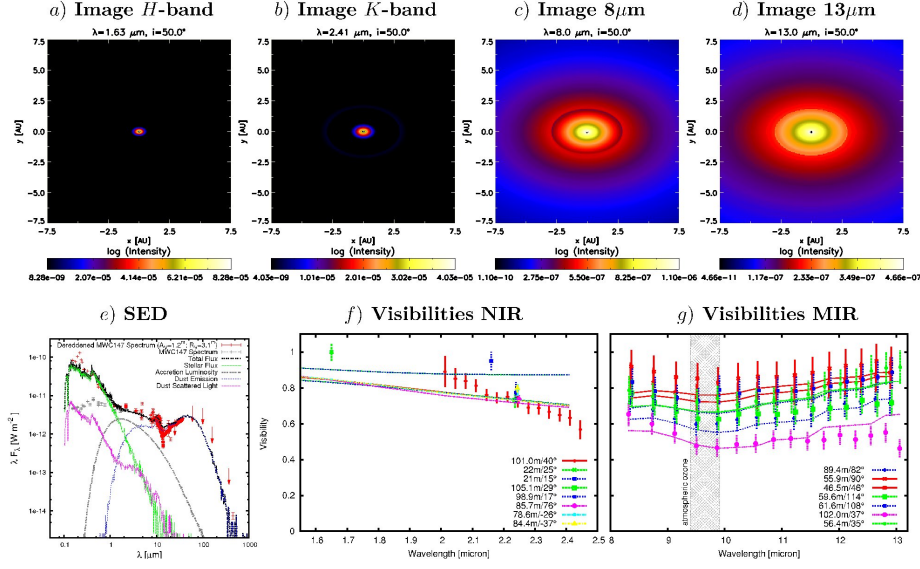


Fig. 4. Observables corresponding to our best-fit radiative transfer model with optically-thick inner gas disk (similar to Fig. 3), yielding good agreement ($\chi_r^2 \approx 1.0$).

wavelength range from 2 to $13 \mu\text{m}$. We find evidence that the NIR emission of MWC 147 is dominated by the emission from optically-thick gas located inside the dust sublimation radius, while the MIR also contains contributions from the outer, irradiated dust disk.

Our study demonstrates the power of infrared spectro-interferometry to probe the inner structure of the disks around young stars and to disentangle multiple emission components. Future investigations on YSO accretion disks will benefit substantially from the proposed 2nd generation VLTI instruments, such as MATISSE, increasing not only the number of recorded baselines, but also expanding the spectral coverage to the L and M bands.

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